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A RIVER ENVIRONMENT RELATIVE COMPARISON MODEL BASED ON THE RANKING USING MULTIPLE WATER QUALITY INDICATORS

*Shengping Zhang[1] and Jie Qi[2]

[1]Faculty of Urban Science, Meijo University, Japan; [2]School of International Studies, Utsunomiya University, Japan

*Corresponding Author, Received: 08 July 2023, Revised: 14 July 2024, Accepted: 18 July 2024

ABSTRACT: This study aims to develop a comprehensive river environment comparison model for the 109 Class-A watersheds in Japan, which are designated as the most important watersheds and are under the jurisdiction of the Japanese Central Government. River environmental comparison is essential for river management and prioritization of environmental improvement. Over the last 50 years, the river environmental comparison in Japan has been based on a single water quality indicator, BOD, due to organic pollution being the most serious water quality issue. However, a comprehensive comparison model that considers multiple water quality indicators is needed as organic pollution has been largely controlled. This study develops a statistical comparison model by ranking the rivers with multiple environmental indicators and defines an Evaluation Score (ES) using the Multivariate Distribution Theory. The verification process has demonstrated this comparison model is reliable and valid. This model is also capable of identifying the causes of low ranking and the effective measures to improve the ranking. This study is expected to contribute to the establishment of a more reliable river environmental planning and management methodology.

Keywords: River Environment Evaluation, Water Quality Indicators, Multiple-Indicator-Based Ranking, Statistical Model, Multivariate Distribution Theory

1. INTRODUCTION

Evaluating and ranking the river environment quality is essential for accurately understanding the current status of the river environment quality within a country or region, as well as for selecting the target rivers that should be prioritized for improvement and determining the level of improvement. The methodology for ranking river environment quality can vary depending on the country and organization that is conducting the ranking.

In Japan, the Ministry of Land, Infrastructure, Transport, and Tourism has been evaluating the river environment quality under its jurisdiction every year since 1971 and announcing the results as a ranking [1]. The ranking is based on simply adopting Biochemical Oxygen Demand (BOD) as a water quality index. BOD was adopted because organic matter pollution was serious in the past. However, even though the pollution by organic matter has been considerably improved since then, the Japanese government has continued to use only BOD for river environment quality ranking until today without any change.

Evaluating and ranking river environment based on a single water quality indicator is clearly insufficient to accurately understand the river environment, and evaluation using multiple water quality indicators is indispensable. A lot of studies on multiple-indicator-based evaluation have been reported [2-4]. For example, the Ministry of the Environment of Japan has adopted five water quality indicators, including Hydrogen-ion Concentration (pH), BOD, Suspended Solids (SS), Dissolved Oxygen (DO), and Total Coliform (TC) in the River Water Quality Environmental Standards established to protect the living environment [5]. In Malaysia, the Department of Environment (DOE) determines river environment quality with a combined Water Quality Index (WQI) [6]. WQI is defined by six factors: DO, BOD, COD, SS, ammoniacal nitrogen (NH_3-N), and pH.

However, environmental evaluation using multiple water quality indicators makes it difficult to rank them comprehensively. If multiple indicators are statistically independent of each other, there is no need to integrate them, and ranking by each indicator makes sense. On the other hand, if multiple indicators are completely dependent, they are nothing but different expressions of the same thing, and ranking by any one of them is sufficient. As many studies have already shown, multiple water quality indicators have a certain degree of statistical correlation, and their relationship is neither completely independent nor completely dependent [7,8]. This fact makes it difficult to rank river environments using multiple water quality indicators.

The simplest way to solve the problem of river environmental ranking using multiple water quality indicators is to combine them into a single indicator by weighting them. This method has been adopted and widely applied around the world [9,10]. This method is also used in fields other than water environmental evaluation. For example, in the world's urban safety assessment, multiple safety indicators are added together with a weight coefficient of 1 for each to produce a comprehensive ranking of safe cities [11].

The method of assigning weights to individual indicators and calculating a composite evaluation value has the remaining challenge of finding the basis for weighting. The studies mentioned above implicitly assigned weights as if they were common sense without explicitly showing their basis. Some studies recognized this problem and used an artificial intelligence model to find the basis in the correlation among indicators [6,12-14], but the teacher/training data used to construct the artificial intelligence model was created based on the researchers' experience and perception, and the arbitrariness was still not eliminated. Thus, it is clear that there is a fatal flaw in the method of assigning weights to individual evaluation indicators and calculating a composite evaluation value. In this study, we propose a fundamentally different comprehensive evaluation model for a multiple-indicator-based water environment from conventional studies.

2. RESEARCH SIGNIFICANCE

In this study, we proposed a statistical water environment evaluation and ranking model that incorporates the internal structure of data, including the correlation among multiple water quality indicators, based on the principle of "letting the data speak for themselves" and eliminating all human arbitrary judgments. Specifically, we constructed an environmental evaluation and ranking model using Multivariate Distribution Theory, verified the reliability of the proposed model using reliable data, and applied this model to evaluate the Class-A rivers in Japan, and analyzed and discussed the evaluation results. As a result, the validity of the statistical model proposed in this study was clarified.

3. MULTIVARIATE DISTRIBUTION THEORY

Multivariate Distribution Theory is a well-studied branch of statistical mathematics. As in the case of river environment evaluation dealt with in this study, which requires consideration of multiple water quality indicators, many application fields of statistics require dealing with multiple variables. Here, the problem is how to handle the relationship among multiple variables, and Multivariate Distribution Theory provides the basis for model construction in such cases. An overview of Multivariate Distribution Theory is provided as follows.

3.1 Definition of A Multivariate Distribution

Multivariate distributions show comparisons between two or more measurements and the relationships among them. For each univariate distribution with one random variable, there is a more general multivariate distribution. For example, the normal distribution is univariate and its more general counterpart is the multivariate normal distribution, while the multivariate normal model is the most commonly used model for analyzing multivariate data.

If the variables are continuous, the multivariate distribution of an N-dimensional variable set $\boldsymbol{x} = (x_1, \cdots, x_N)^{\boldsymbol{T}}$ is described by a density function $f(x_1,\cdots, x_N)$ which satisfied [15,16]

$$\int_{-\infty}^{+\infty} \cdots \int_{-\infty}^{+\infty} f(x_1,\cdots, x_N) dx_1 \cdots dx_N = 1 \tag{1}$$

There are a variety of multivariate distributions that are well-studied and severed properly for the density function $f(x_1,\cdots, x_N)$ such as gamma distribution, logarithmic distribution, and normal distribution. A fitting process is usually required to decide which distribution serves a specific data set the best. However, a fitting process could be very complicated and is usually skipped by directly choosing the normal distribution, which is partially justified by the famous Central Limit Theorem [17]. The following section is the details of a multivariate normal distribution.

3.2 A Multivariate Normal Distribution

A Multivariate Normal Distribution of an N-dimensional variable set $\boldsymbol{x} = (x_1; \cdots; x_N)^{\boldsymbol{T}}$ is expressed as follows [18].

$$\mathcal{N}(\boldsymbol{x}|\boldsymbol{\mu}, \Sigma) = \frac{1}{\sqrt{(2\pi)^N \det(\Sigma)}} \exp\left(-\frac{(\boldsymbol{x}-\boldsymbol{\mu})^T \Sigma^{-1} (\boldsymbol{x}-\boldsymbol{\mu})}{2}\right) \tag{2}$$

Where $\mathcal{N}(\boldsymbol{x}|\boldsymbol{\mu}, \Sigma)$ is an N-dimensional distribution density function, vector $\boldsymbol{\mu}$ is the mean of the variable set $\boldsymbol{x} = (\boldsymbol{x_1}; \cdots; \boldsymbol{x_N})^{\boldsymbol{T}}$, and the covariance matrix of the variable set is Σ. The determinant and the inverted matrix of the covariance matrix $\sum$ are $\det(\sum)$ and $\sum^{-1}$, respectively. $\sum$ will be a unit matrix when all the variables in $\boldsymbol{x} = (\boldsymbol{x_1}; \cdots; \boldsymbol{x_N})^{\boldsymbol{T}}$ are independent.

4. EVALUATION SCORE

In the following, we will apply this Multivariate Distribution Theory to river environment evaluation and ranking. Before that, a reliability check has been made for the multivariate distribution model.

4.1 Definition of Evaluation Score

In order to apply the above multivariate distribution theory to water environment evaluation based on multiple water quality indicators, we define a water environment evaluation score based on the multivariate distribution. In this study, we define the evaluation score $ES(\mathbf{x}(0))$ as the probability by that a specific water quality level $\boldsymbol{x}(0) = (x_1(0); \cdots; x_N(0))^{\boldsymbol{T}}$ is realized. This definition is formulated as follows.

$$ES(\mathbf{x}(0)) = \int_{-\infty}^{x_1(0)} \cdots \int_{-\infty}^{x_N(0)} \mathcal{N}(\boldsymbol{x}|\boldsymbol{\mu}, \textstyle\sum) dx_1 \cdots dx_N \qquad (3)$$

The evaluation score (ES) defined in this way expresses how difficult it is to achieve a combination of current levels of each indicator in terms of their probability of realization. One should be careful about the meaning and interpretation of this probability. This is because, as can be seen by imagining the shape of the probability density function of a one-dimensional normal distribution, the effect of a small change in the variable around the mean value and a small change around ±2σ on the realization probability are very different and incomparable. However, this realization probability is suitable for relative comparison of the difficulty of achieving the current level of the random variables, and is an appropriate indicator for ranking the current level of the random variables.

4.2 Examination of Evaluation Score Model

We applied the evaluation score model to an urban security problem with a reliable data record to examine the reliability of the model.

The Economist Intelligence Unit, a research subdivision of the renowned and authoritative magazine The Economist, published a report titled "Safe Cities Index 2019−Urban Security and Resilience in an interconnected world" in September 2019 [19]. The report ranked 60 major cities worldwide based on 57 indicators covering Digital Security, Health Security, Infrastructure Security, and Personal Security. Each security area received a score ranging from 0 to 100 according to the expertise and views of the specialists in the field. Finally, a general city security index, The Safe Cities Index (SCI), was calculated as the simple average of the scores for the four security areas.

This is a typical multivariate ranking problem, and The Economist Intelligence Unit created the comprehensive ranking score by simply combining the four security indicators with equal weights. In this study, we used the evaluation score proposed above to rank the cities and to compare their performance with the SCI method [20].

Table 1 has compared the ranking results of the 60 major cities based on the SCI and ES scores, the details of which is shown in Table 2.

There were significant changes observed from Table 2. Firstly, the title of the safest city has shifted from Tokyo to Singapore. In the rankings based on the ES score, Wellington, Paris, Stockholm, and Copenhagen saw substantial improvements in their positions, while Washington DC, Moscow, and New York City experienced declines. Although these results align with the intuition of many, further evidence is required to confirm that these ranking changes reflect a closer approximation to reality.

To compare the two evaluation methods and identify which one is better, we used the correlation coefficient between the evaluation score obtained by each method and the four evaluation indicators as a comparison criterion. A higher correlation coefficient means a more rational evaluation method that reflects the internal structure of the data better.

Table 1 shows the comparison results of the correlation coefficients obtained by both evaluation methods. the Evaluation Score (ES) proposed in this paper has higher correlations with the four evaluation indicators than the SCI used by The Economist, and can be said to reflect the original structure of the data more accurately. In the next section, we will apply this evaluation score model to the ranking of Class-A rivers in Japan.

Table 1 Correlation coefficient comparison

	Digital Security	Health Security	Infrastructure Security	Personal Security
SCI	0.946	0.906	0.942	0.848
ES	0.955	0.962	0.975	0.912

5. RANKING CLASS-A RIVERS OF JAPAN

5.1 Class-A Rivers

Japan has 109 important rivers, which have a very

Table 2 City security ranking results by both SCI and ES

City	SCI		ES		Ranking Changes	City	SCI		ES		Ranking Changes
	Score	Ranking	Score	Ranking			Score	Ranking	Score	Ranking	
Tokyo	92.0	1	0.806	2	-1	Beijing	70.5	31	0.285	33	-2
Singapore	91.6	2	0.808	1	+1	Shanghai	70.2	32	0.274	34	-2
Osaka	90.9	3	0.788	3	0	Santiago	69.9	33	0.312	31	+2
Amsterdam	88.0	4	0.747	4	0	Buenos Aires	69.7	34	0.292	32	+2
Sydney	88.0	4	0.739	6	-2	Kuala Lumpur	66.3	35	0.21	35	0
Toronto	87.8	6	0.726	7	-1	Istanbul	66.2	36	0.158	38	-2
Washington DC	87.6	7	0.671	12	-5	Moscow	65.8	37	0.090	45	-8
Seoul	87.5	8	0.714	9	-1	Kuwait City	64.5	38	0.179	36	+2
Copenhagen	87.4	9	0.741	5	+4	Riyadh	62.5	39	0.161	37	+2
Melbourne	87.3	10	0.708	10	0	Mexico City	61.6	40	0.115	42	-2
Chicago	86.7	11	0.646	15	-4	Rio de Janeiro	60.9	41	0.138	39	+2
Stockholm	86.5	12	0.722	8	+4	Sao Paulo	59.7	42	0.115	41	+1
San Francisco	85.9	13	0.636	16	-3	Manila	59.3	43	0.118	40	+3
London	85.7	14	0.655	14	0	Johannesburg	58.6	44	0.089	47	-3
New York	85.5	15	0.607	21	-6	Mumbai	58.3	45	0.098	44	+1
Frankfurt	85.4	16	0.666	13	+3	Lima	58.2	46	0.110	43	+3
Los Angeles	85.2	17	0.587	22	-5	Ho Chi Minh City	57.7	47	0.064	49	-2
Wellington	84.5	18	0.673	11	+7	Bangkok	57.6	48	0.089	46	+2
Zurich	84.5	18	0.617	18	0	Baku	56.4	49	0.072	48	+1
Hong Kong	83.8	20	0.615	19	+1	Quito	55.3	50	0.056	51	-1
Dallas	83.1	21	0.587	23	-2	Bogota	55.1	51	0.034	54	-3
Paris	82.5	22	0.624	17	+5	New Delhi	55.0	52	0.052	53	-1
Taipei	82.5	22	0.614	20	+2	Jakarta	54.5	53	0.059	50	+3
Brussels	82.1	24	0.585	24	0	Casablanca	53.5	54	0.056	52	+2
Madrid	81.4	25	0.507	28	-3	Cairo	48.6	55	0.028	55	0
Barcelona	81.2	26	0.504	29	-3	Dhaka	44.7	56	0.017	56	0
Abu Dhabi	79.5	27	0.539	25	+2	Karachi	43.5	57	0.005	58	-1
Dubai	79.1	28	0.519	26	+2	Yangon	41.9	58	0.007	57	+1
Milan	78.2	29	0.510	27	+2	Caracas	40.1	59	0.003	59	0
Rome	76.4	30	0.426	30	0	Lagos	38.1	60	0.001	60	0

large impact on various fields such as flood control, water use, and environmental conservation, and require careful management. Therefore, all these rivers are under the jurisdiction of the central government's Minister of Land, Infrastructure, Transport and Tourism, and are called Class-A rivers. When deciding on the measures and budget necessary for managing these rivers, it is necessary to evaluate the current situation of each river in an easy-to-understand way for decision-making officers such as parliament members, and based on the evaluation results, the improvement priority and budget are determined. The most straightforward way to evaluate the current situation is to rank the rivers according to their environmental conditions. In fact, almost every year, a special environmental improvement budget has been allocated to the rivers that ranked in the worst 10 [21].

However, until now, the ranking has been done only by a single indicator BOD, which is inconsistent with the river water quality environmental standards established by the same Japanese government. The river water quality environmental standards set five water quality indicators including pH, BOD, SS, DO, and Total Coliform (see Table 3) as the goals for environmental management [5]. Clearly, ranking based solely on BOD is inappropriate and insufficient. In this study, we apply the evaluation score model proposed in the previous section to rank these Class-A rivers.

5.2 Applying the ES Model to Class-A Rivers

We used the data from the water quality survey of the 109 Class-A rivers to rank the river environment by applying the proposed evaluation score model. The data are available in an open-source database maintained by the Ministry of Land, Infrastructure, Transport and Tourism of Japan [22]. We excluded 5 rivers from the analysis due to missing data and selected 104 rivers for the final data set. The data cover the 5 water quality indicators pH, BOD, SS, DO, and TC for a period of 5 years from 2014 to 2018, and there is one data record for each month.

Considering the purpose of this study to verify the validity of the proposed ranking model, we decided to use the 5-year-long average values of the water quality data to eliminate the effects of sudden water quality changes in the short term and random measurement errors. Table 4 shows the Evaluation

Table 3 Water environment quality standards for rivers [5]

Item Class	Water Use	Standard Value: Hydrogen-ion Concentration (pH)	Biochemical Oxygen Demand (BOD)	Suspended Solids (SS)	Dissolved Oxygen (DO)	Total Coliform (TC)
AA	Water supply class 1, conservation of natural environment, uses listed in A-E	6.5≤pH≤8.5	≤1 mg/L	≤25 mg/L	≥7.5 mg/L	≤50MPN/100mL
A	Water supply class 2, fishery class 1, bathing and uses listed in B-E	6.5≤pH≤8.5	≤2 mg/L	≤25 mg/L	≥7.5 mg/L	≤1000MPN/100mL
B	Water supply class 3, fishery class 2, and uses listed in C-E	6.5≤pH≤8.5	≤3 mg/L	≤25 mg/L	≥5.0 mg/L	≤5000MPN/100mL
C	Fishery class 3, industrial water class 1, and uses listed in D-E	6.5≤pH≤8.5	≤5 mg/L	≤50 mg/L	≥5.0 mg/L	-
D	Industrial water class 2, agriculture water, and uses listed in E	6.0≤pH≤8.5	≤8 mg/L	≤100 mg/L	≥2.0 mg/L	-
E	Industrial water class 3 and conservation of environment	6.0≤pH≤8.5	≤10 mg/L	Floating matter such as garbage should not been observed	≥2.0 mg/L	-

Table 4 The evaluation score (ES), ranking results by ES and individual water quality indicators

ES	Ranking by ES	pH	BOD	SS	DO	TC	ES	Ranking by ES	pH	BOD	SS	DO	TC
0.995	1	1	2	2	1	1	0.589	53	59	51	49	49	55
0.978	2	5	1	1	4	3	0.573	54	53	55	55	55	51
0.976	3	3	4	7	3	4	0.570	55	46	54	51	56	58
0.976	4	4	5	4	5	6	0.567	56	49	52	56	53	56
0.966	5	10	3	3	2	2	0.550	57	63	57	57	57	53
0.964	6	7	8	8	6	9	0.547	58	50	58	60	60	61
0.957	7	13	6	5	8	8	0.546	59	54	62	61	62	60
0.954	8	2	9	10	9	10	0.515	60	64	59	65	58	62
0.952	9	16	7	9	7	11	0.507	61	60	60	59	61	63
0.943	10	11	11	12	11	7	0.491	62	61	61	58	59	59
0.940	11	8	12	11	12	5	0.487	63	65	63	63	63	57
0.938	12	20	10	6	10	12	0.466	64	57	65	67	66	71
0.928	13	6	15	14	13	17	0.458	65	62	68	64	68	67
0.920	14	12	14	18	14	19	0.448	66	67	64	66	65	64
0.916	15	14	13	13	15	13	0.441	67	66	66	62	64	72
0.912	16	9	20	16	18	26	0.435	68	73	67	68	67	65
0.901	17	15	17	17	19	14	0.431	69	68	71	70	70	66
0.891	18	17	16	19	16	20	0.430	70	70	69	71	69	75
0.886	19	24	18	21	17	21	0.408	71	77	73	74	73	69
0.876	20	18	19	15	20	24	0.395	72	75	70	72	72	68
0.872	21	26	21	22	21	15	0.394	73	74	72	69	71	76
0.864	22	23	23	26	22	28	0.375	74	69	78	77	78	78
0.846	23	27	22	20	23	22	0.369	75	71	74	80	74	73
0.837	24	19	24	24	24	30	0.364	76	85	75	73	76	70
0.834	25	21	25	27	26	23	0.363	77	76	76	75	75	85
0.833	26	30	27	28	25	16	0.353	78	72	77	76	77	82
0.829	27	22	30	25	30	25	0.352	79	81	79	79	81	79
0.827	28	31	28	32	27	18	0.340	80	78	80	78	82	86
0.824	29	28	29	30	28	31	0.336	81	87	82	83	80	74
0.796	30	33	26	23	29	34	0.312	82	79	83	84	88	90
0.783	31	29	31	31	33	27	0.299	83	80	86	82	86	80
0.765	32	25	33	33	32	40	0.292	84	88	85	87	83	84
0.756	33	39	32	29	31	33	0.291	85	91	81	81	79	87
0.756	34	36	36	35	35	38	0.271	86	86	84	86	85	83
0.756	35	37	37	41	36	29	0.253	87	82	88	85	87	91
0.753	36	32	34	40	34	42	0.247	88	94	87	91	84	77
0.730	37	41	35	38	39	37	0.229	89	83	89	89	89	92
0.725	38	35	38	36	37	41	0.222	90	92	90	90	90	81
0.698	39	47	39	34	40	32	0.213	91	84	92	88	93	96
0.698	40	42	42	42	42	36	0.163	92	93	93	96	91	93
0.696	41	40	40	45	38	35	0.150	93	96	91	93	92	95
0.683	42	34	41	37	41	45	0.124	94	89	97	98	95	94
0.681	43	51	43	39	43	39	0.113	95	101	94	97	94	88
0.677	44	38	45	46	44	48	0.088	96	102	95	92	97	89
0.675	45	45	46	44	45	46	0.080	97	90	99	95	96	97
0.675	46	55	44	43	46	44	0.068	98	100	98	94	100	99
0.664	47	43	47	47	47	43	0.050	99	99	96	99	98	100
0.651	48	48	48	50	48	52	0.044	100	103	100	102	99	101
0.633	49	56	50	48	52	47	0.038	101	98	102	101	102	98
0.627	50	52	53	52	50	50	0.037	102	97	101	100	101	104
0.622	51	58	49	54	51	54	0.013	103	95	103	104	103	102
0.617	52	44	56	53	54	49	0.005	104	104	104	103	104	103

Score (ES) and the ranking based on ES for the 104 Class-A rivers, as well as the ranking when each indicator of pH, BOD, SS, DO, and Total Coliform (TC) was evaluated separately.

Since different rankings are obtained by different indicators, we calculated two different kinds of Average Deviation (AD) between the two rankings $R_a(i)$ and $R_b(i)$ as follows to compare the ranking results.

$$AD_a(i) = \frac{\sum_b |R_a(i) - R_b(i)|}{5} \quad (4)$$

$$AD_{a,b} = \frac{\sum_{i=1}^{104} |R_a(i) - R_b(i)|}{104} \quad (5)$$

Where (i) indicates river number, and a, b are different water quality indicators. $AD_a(i)$ is the average deviation of river (i)'s ranking by indicator a from all the other five indicators, and $AD_{a,b}$ is the average deviation between two different water quality indicators for all 104 rivers.

$AD_{a,b}$ is shown in Table 5. The average value of the total deviation from all other rankings is shown in the last row of each column of the same table, and visualized as in Fig. 1. Clearly, the rankings based on pH and TC differ significantly from other ranking results and lack representativeness as a comprehensive evaluation. The assessments based on ES, BOD, and DO are relatively closer, with the evaluation based on ES being the most representative. This finding is entirely consistent with the results observed for each river's $AD_a(i)$ as shown in Fig.2.

Table 5 Comparison of ranking deviation $AD_{a,b}$ between different ranking indicators

	ES	pH	BOD	SS	DO	TC
ES	0	3.90	1.29	2.13	1.31	3.46
pH	3.90	0	4.48	4.56	4.48	6.21
BOD	1.29	4.48	0	2.08	1.10	3.79
SS	2.13	4.56	2.08	0	2.38	4.10
DO	1.31	4.48	1.10	2.38	0	3.79
TC	3.46	6.21	3.79	4.10	3.79	0
Average AD	2.42	4.73	2.55	3.05	2.61	4.27

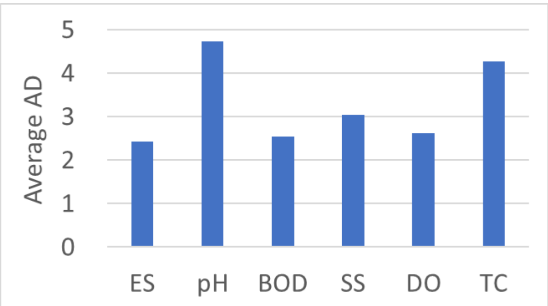

Fig. 1 Average $AD_{a,b}$ of different ranking indicators for all rivers

5.2 Result Discussion

The following can be derived from the ranking results above.

First, the ranking results by different indicators and methods are different but quite close (see Table 4). There was no significant reversal in the rankings by different indicators. This is considered to be due to the fact that the data used for the ranking are the 5-year average water quality. The 5-year average water quality data almost completely exclude the short-term fluctuations in water quality and only retain the long-term fluctuation characteristics. This can also be seen from the high correlation coefficients between the five evaluation indicators (see Table 6).

Next, as shown in Table 5, the evaluation based on ES has the smallest average deviation of 2.42 from the other ranking results, and it can be said that the ranking based on ES is relatively the most reliable of the compared models. This also can be confirmed with the fact shown in Fig.2 that ES has the lowest average deviations for almost all rivers. This indicates the validity of the evaluation method proposed in this study.

Furthermore, among the rankings based on single indicators, the evaluation based on BOD is the best, followed by the evaluation based on DO. On the other hand, the rankings based on pH and TC have larger deviations from the other evaluation results than BOD and DO, which are considered to be due to the characteristics of these two indicators themselves that both pH and TC are much easier to be affected by a single rainfall or urban drainage system overflow event.

Finally, we discussed the reliability of the proposed model by using the ranking deviation as a model evaluation criterion. The ranking deviation is a relative value, but since there is no absolute or right ranking for the river environment data consisting of many water quality indicators, absolute evaluation is impossible. Considering all these facts and factors, it is reasonable to conclude that the comprehensive evaluation and ranking method of the river environment proposed in this

Table 6 Correlation coefficients of water quality indicators in absolute value

	pH	BOD	SS	DO	TC
pH	1	0.88	0.77	0.90	0.62
BOD	0.88	1	0.87	0.92	0.68
SS	0.77	0.87	1	0.86	0.70
DO	0.90	0.92	0.86	1	0.65
TC	0.62	0.68	0.70	0.65	1

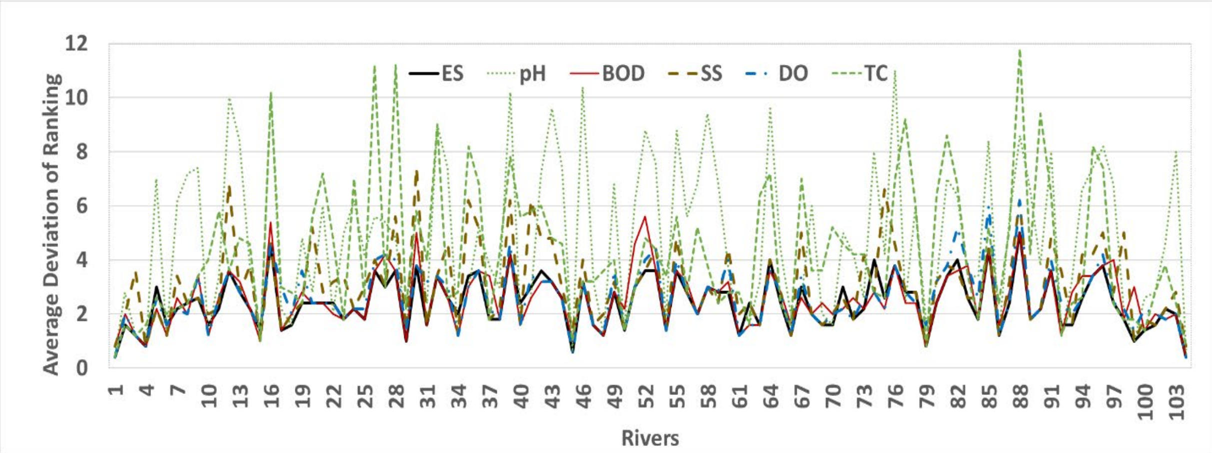

Fig. 2 Average deviation $\boldsymbol{AD_a(i)}$ of ranking for each river

study, using the evaluation score (ES) defined by applying the multivariate distribution to water quality indicators, is reliable and effective.

5. CONCLUSION

In this paper, we constructed an evaluation score model using Multivariate Distribution Theory and ranked the river environments described with multiple water quality indicators by applying this model. Multivariate Distribution Theory is a natural extension of the stochastic distribution theory for a single random variable, but it is difficult to handle the distribution function, and it has not been widely applied in water environment engineering fields.

To verify the reliability of the constructed model, we used the urban security evaluation problem, which has reliable data and has been well-studied by the renowned magazine The Economist. The verification results showed the reliability and validity of the proposed model.

Then, we applied the verified model to 104 Class-A rivers in Japan and compared the ranking results by the proposed model with those by the conventional individual water quality indicators. As a result, we found that the proposed model provided the most rational and reliable river environment ranking results among all the studied models.

The most significant character of this evaluation score model is that the evaluation and ranking are completely based on the raw water quality records used in the evaluation without any kinds of artificial water quality standards or human judgements involved. This is because of the model-developing principle of "letting the data speak for themselves". We are not claiming that an evaluation model without any human judgements is better, but we do believe that an evaluation model purely based on water quality data is necessary as a reference even when we use evaluations with human judgements such as the evaluation based on the widely-applied Water Environment Quality Standards for rivers that are established by the Japanese central government.

The proposed model has high generality and can be applied to many multivariate evaluation problems. In the future, further verification of the reliability and validity of the proposed model by increasing the application examples, and the evolution and development of research utilizing this model are expected.

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